

Recent Results from the LHC Inner Triplet Quadrupole Development Program at Fermilab

N. Andreev, T.T. Arkan, P. Bauer, R. Bossert, J. Brandt, D.R. Chichili, J. Carson, J. DiMarco, S. Feher, J. Kerby, M.J. Lamm, P.J. Limon, A. Makarov, A. Nobrega, I. Novitski, T. Ogitsu, D. Orris, J.P. Ozelis, W. Robotham, G. Sabbi, P. Schlabach, J. Strait, M. Tartaglia, J.C. Tompkins, S. Yadav, A.V. Zlobin
Fermilab, Batavia, IL, USA

S. Caspi, A.D. McInturff, R. Scanlan
Lawrence Berkeley National Laboratory, Berkeley, CA, USA

A. Ghosh
Brookhaven National Laboratory, Upton, NY, USA

Abstract--Fermilab, in collaboration with LBNL and BNL, is in the process of developing a focusing quadrupole for installation in the interaction region inner triplets of the LHC. This magnet is required to have an operating gradient of 215 T/m across a 70mm coil bore, and operates in superfluid helium at 1.9K. The design is based on a two layer cos (2π) coil, mechanically supported by standalone steel collars. The collared coil assembly is surrounded by a iron yoke for flux return, and the assembly enclosed by a stainless steel shell. The development program has addressed mechanical, magnetic, quench protection, and thermal issues, through a series of model magnets constructed at Fermilab. This paper summarizes results from the recent model tests, and the status of the program.

I. INTRODUCTION

The LHC Interaction Region inner triplets consist of four 70mm single aperture quadrupoles (MQX), which are required to achieve a field gradient of 215 T/m during machine operation. Fermilab has led a collaboration which developed a design meeting the machine requirements, and will produce half of the quadrupoles to be installed at the four LHC interaction points.

An R&D program including the construction of a series of 2m long model magnets (HGQ) was started several years ago, to prove the design before moving to the construction of a full length prototype. The baseline design has been previously reported [1,2], as have complete results from the first three model magnets [3]. Test results through magnet HGQ03 showed serious quench performance problems, at which time several important changes were introduced in the magnet design, and the program modified to include three additional model magnets. Partial results from the first magnet incorporating these changes were reported this past spring [4], including a significant improvement in the quench performance. This paper reports the results from magnets HGQ05, HGQ06, and from HGQ07 which is currently under test.

II. MAGNET DESIGN AND FABRICATION

A. Design Modifications

After the disappointing quench performance of the first three model magnets, a set of changes were introduced starting with magnet HGQ05 which addressed the issues seen in the previous models. The changes focused on improvement of the coil end region, improved stability of the collar structure, optimization of the azimuthal prestress, particularly in the body/end transition, and better matching of the inner and outer coil properties. Specifically these changes, applied to all models, included:

- use of G10/G11 as the end part material
- use of solid collar packs, filling the pole regions
- end can assemblies over both ends
- optimization of the coil prestress
- matching the inner and outer coil properties to minimize shear potential between coil layers
- attachment of the ends to the end plates, controlling the displacement of the collared coil during cooldown and excitation

Table I summarizes the detail changes introduced in model magnets HGQ05-07. Three different types of inner cable have been used in HGQ05 through HGQ07, to gather data for the final choice of cable to be used in production. All have used existing SSC strands, and have been cabled to the same target dimensions. The desire to use left lay inner cable in the production magnets was driven by the availability of enough existing strand of left twist for all production needs, while the use of right lay cable requires the purchase of 4 new billets of wire to SSC specifications. Reducing the strand count in the inner cable was proposed to decrease the cable packing factor to less than 90%, and short sample tests on 37 strand cable showed no change in I_c compared to 38 strand cable. On HGQ06 and HGQ07 we used a polyimide adhesive, as this can be applied in a more controlled manner to the Kapton, and is less susceptible to flow and fill cooling channels during the cure cycle. This modification requires an increase in the cure temperature to 190 C. Finally, after HGQ05, the '5 block' end design was introduced, the difference being that the large conductor block of the inner coil end was split into two smaller groups, to improve the end support of those turns. In previous magnets, concerns over the relative softness of this

region of the coil end and possible poor support in this region led to this modification.

TABLE I
INNER CABLE AND COIL CURING PARAMETERS

	HGQ05	HGQ06	HGQ07
Cable Lay	Right	Left	Left
# Strands	38	38	37
Insulation Adhesive	Epoxy	Polyimide	Polyimide
Cure Temperature	135 C	190 C	190 C
End Design	4 block	5 block	5 block

B. Fabrication Experience

The introduction of left lay inner cable in HGQ06 and HGQ07 has led to a greater rejection rate of coils. The left lay inner cable must be wound in the unfavorable direction, and is therefore less stable. Upon inspection after curing about 25% of the coils made with left lay cable have been rejected due to popped strands, typically around the exit region of the inner coil key. The reduction in number of strands has not produced any ill effects in the coil production process. Details of recent coil fabrication experience are reported elsewhere [5].

A high pressure cure was used on all coils, accomplished by decreasing the curing mold size while curing to a fixed cavity size. This change was introduced for two reasons: first, the azimuthal modulus of the cured inner coils used in previous magnets, and the pressure necessary to close the curing mold were both low. Typically it is preferred that the coil be cured at a pressure higher than it experiences during operation to minimize insulation creep effects. Also, it was desired to better match the properties of the inner and outer coils, to reduce potential shear effects generated during excitation. Increasing the cure pressure of the inner coils to that similar to the outer coils accomplished both of these conditions.

Mechanical measurements of the prestress achieved after collaring, by gauges and diametrical measurements of the collared coil, show that over this set of magnets we have consistently achieved our prestress targets [6]. Local shimming of the mold cavity has reduced the systematic component of the coil size variation and decreased the range in coil preload seen in the assembled magnet. A coil size range of 50 microns about the target value as measured at azimuthal pressures similar to those observed in the collared coil assembly was previously reported. In recent models a range of 35 microns has been achieved by the introduction of a modest shim to the curing mold, corresponding to measurement locations in the previous cured coils which were systematically larger than others.

To restrict the end motion in HGQ05 and HGQ06 we attached the end cans to the end plates of the magnet during final assembly, such that the coil is stretched slightly at room temperature, and stretches further with cooldown. The end saddles of the coils remain in contact with the bullet gauges attached to the end plate as well. During a 3rd thermal cycle of HGQ05, we removed this end restriction to investigate the effect on quench performance. HGQ07 has been initially assembled and tested in the first two thermal cycles without

end load, and will be tested in a 3rd thermal cycle with end restraint to give a complementary set of quench performance data. We expect however to restrain the ends in production as it gives a direct means of controlling the magnet length during operation.

In earlier magnets through HGQ06, a mechanical twist of on the order 1mrad/m was measured. Through optimization of the yoke and skinning assembly and weld process the twist in a mechanical model and in HGQ07 measures less than 0.2mrad/m.

III. TEST RESULTS

A. Quench Performance

In LHC the inner triplet quadrupoles will operate at a gradient up to 215 T/m at a ramp rate of 10 A/s. For each production magnet, the quench performance goals are that the magnet train to at least 230 T/m during the 1st thermal cycle, and then have an initial quench in the 2nd thermal cycle at 220 T/m.

The quench performance of HGQ05 through HGQ07, in each of the first two thermal cycles at 1.9K of testing is shown in Fig. 1, and is reported in more detail elsewhere [7]. Previous to the first thermal cycle shown here each magnet has had on the order of 10 quenches at 4.3K, where HGQ05 and HGQ07 reached their short sample limit very quickly, while HGQ06 trained more slowly and only achieved 93% of short sample after 14 quenches. At 1.9K all three magnets reach the required 230 T/m training goal in eight or fewer quenches, with the initial quenches of HGQ06 and HGQ07 being above the operating gradient of 215T/m. After a thermal cycle, both HGQ05 and HGQ07 show training memory better than the goal of 220 T/m, while HGQ06 has a single training quench at 215 T/m before jumping above 230 T/m.

The location of quenches varies somewhat from magnet to magnet. For HGQ05, initial training was dominantly in the

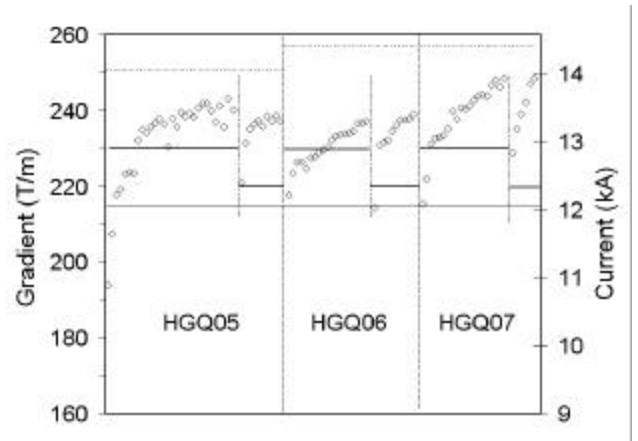


Fig. 1. 1.9K Quenches, 1st and 2nd Thermal Cycles, HGQ05 – HGQ07. Horizontal dashed lines indicate short sample limits for each magnet, continuous solid line the LHC operating gradient, and intermittent solid lines the training goals in the first and second thermal cycles.

outer coil body, near a longitudinal break in the coil wedge, and in a lower prestress region of the coil. In HGQ06, the prestress on the outer coil was raised slightly, and that on the inner coil lowered slightly. All quenches in HGQ06 are in the inner coil body, with many located in turn 11, just below the wedge. As a result, the prestress target at room temperature in HGQ07 was raised on both the inner and outer coils to 70-75MPa, and the initial quenches in HGQ07 are located in the inner coil pole turn. This magnet reaches 230T/m much more quickly than either HGQ05 or HGQ06. Around 235-240 T/m, well above the operating gradient, the quench locations in both HGQ05 and HGQ07 start to vary, and quenches next to the inner coil wedge start to appear. At this force level, we believe the mechanical discontinuity introduced by the wedge to the azimuthal position of the coil turns is sufficient that the continued adequate compression of the coil is difficult.

To date, we have seen no positive correlation between magnet end restraint and quench performance of these magnets.

The magnet temperature dependence was measured in the temperature range of 1.9K – 4.5K, and shows the margin for the inner layer is greater than 2K.

The ramp rate dependence at 1.9K for these three magnets is shown in Fig. 2. For ramp rates less than 100 A/s, the magnet quench current is well above the nominal operating current of 12kA corresponding to a field gradient of 215 T/m. All quenches at lower ramp rates took place in the coil pole regions exposed to the highest field. At higher ramp rates the quenches in HGQ05 were located in the splice region, as in all previous models. In HGQ06 and HGQ07, the high ramp rate quenches originated in the midplane turns, related to the low cable interstrand resistance, a result of the 190 C high pressure cure used on these coils. AC loss measurements and magnetic measurements confirmed the presence of the large eddy current component. This was used to verify experimentally the inner coil turn cooling conditions in the magnet, with a conservative interpretation of the results indicating that the cooling conditions are adequate for an energy deposition of 0.125W/m in the midplane turn of the inner coil, compared to the maximum calculated deposition of 0.08 W/m.

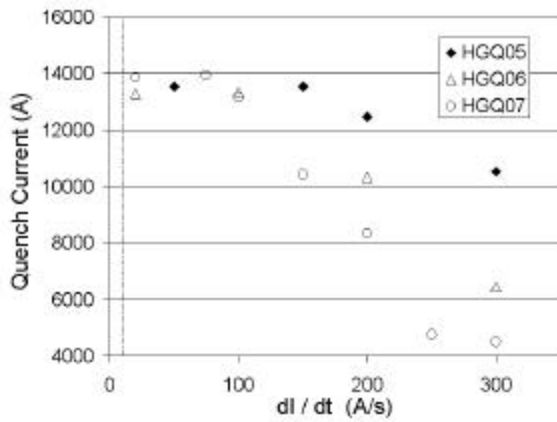


Fig. 2. Ramp Rate Quenches at 1.9K for HGQ05-07. Dashed vertical line represents ramp rate during operation

B. Quench Protection

The quench protection of the magnets, using internal quench heaters only, has been confirmed through a series of tests included in the model magnet program[8]. Starting with HGQ06 a single layer of heaters are installed, between the outer coil and the collars. These heaters are as effective as the baseline design inter coil heaters and much easier to install. Fig. 3 shows the measured peak temperature in spot heater induced quenches, as a function of spot heater location and excitation current. The measured peak temperature is about 300K for the unlikely case of a localized quench in the outer coil midplane, with all other cases being lower. For all cases it is significantly less than the 400K design peak temperature. Based on these studies, the peak voltage to ground in the production magnets will be less than 200V.

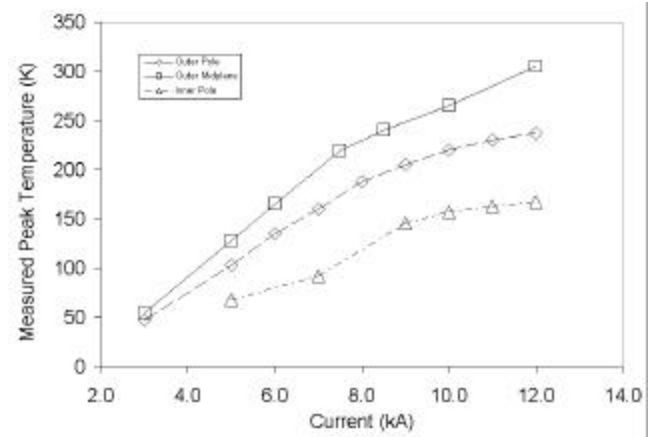


Fig. 3. Measured peak temperature vs. excitation current from spot heater induced quenches.

C. Magnetic Measurements

Table II reports the measured transfer function in T/m/kA as a function of current for all model magnets to date, showing good reproducibility and agreement with calculations. The offset in the measured transfer function in magnets HGQ06-07 is due to the testing of these magnets without tuning shims [9] in the allocated slots, once the decision was taken to remove these from the final design. The final yoke design adds the nominal magnetic component of the shim directly to the lamination.

TABLE II
MEASURED TRANSFER FUNCTION
(T/M/K A)

I, A	HGQ01	HGQ02	HGQ03	HGQ05	HGQ06	HGQ07
750	18.367	18.346	18.357	18.400	18.174	18.161
5750	18.238	18.240	18.228	18.289	18.103	18.079
10750	18.014	18.023	-	18.070	17.960	17.934

The cured coil properties achieved during the production of HGQ05 through HGQ07 have been close enough to our target sizes that only very minimal shims have been necessary to achieve the desired coil prestress. Figure 4 presents the mean and spread, over all model magnets, of the lower order measured harmonics in the body of the magnet, as compared to the reference table used in beam dynamcis simulations of LHC at collision. As has been previously reported, for HGQ01-03 we compare the measured harmonics to the expected harmonics for the ‘as built’ geometry when making this comparison; for HGQ05-07 we have applied no correction due to the cured coil attributes previously mentioned. The data in Fig. 4 show that the model magnets consistently are within the targets. Higher order harmonics not shown in this figure are also all well within targets. A more detailed analysis of the model magnet field quality is presented in [10].

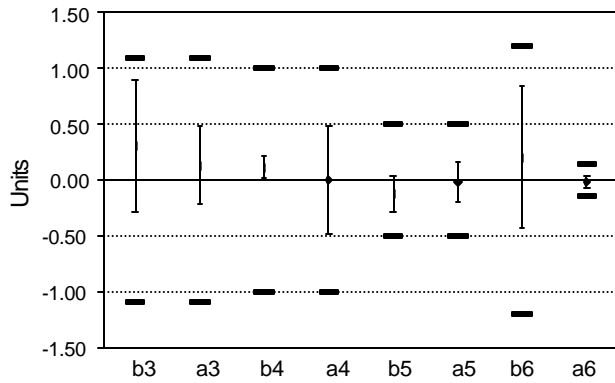


Fig. 4. Measured harmonics over all model magnets compared to reference harmonics table limits. The reference radius is 17mm and harmonics are reported such that b_n and a_n are the $2n$ -pole normal and skew coefficients, respectively.

In HGQ06 and HGQ07 large eddy current harmonics have been measured, consistent with the AC loss measurements. Large differences between harmonics measured during up and down ramps, and increasing with increasing ramp rates, were seen and are summarized in Table III. These effects were not seen in any previous magnet, which included coils for HGQ02-03 made with 190 C, lower pressure cure, and coils for HGQ05 made with a 135 C, high pressure cure.

TABLE III
DIFFERENCE BETWEEN LOWER ORDER FIELD HARMONICS MEASURED ON
THE UP AND DOWN RAMP FOR HGQ06 AT 6kA

n	10A/s		80A/s	
	Δb_n	Δa_n	Δb_n	Δa_n
3	-0.94	-0.43	-6.67	-3.57
4	-0.16	-0.03	-1.19	0.11
5	0.12	0.11	0.86	0.61
6	0.20	-0.03	2.07	-0.23

IV. CONCLUSIONS AND FUTURE WORK

Model magnets HGQ05-07 show a marked improvement in quench performance as compared to earlier model magnets. The performance of the magnets is now more than adequate as compared to the LHC Interaction Region Inner Triplet Quadrupole design requirements. The base mechanical design has been proven sound, and the changes introduced between magnets HGQ05-07 resulted in incremental improvement of the quench performance. The eddy current effect seen in magnets HGQ06-07 will be addressed by a modification of the inner coil cure cycle, including the proper combination of a 190 C, lower pressure step and a 135 C, high pressure step to achieve the desired mechanical and electrical properties in the coils. We have chosen to use right lay inner cable for the prototype and production magnets, based on the coil rejection rate due to popped strands experienced. The last two model magnets will be used to confirm the final design before proceeding to the full length prototype stage next year.

ACKNOWLEDGMENT

The authors would like to acknowledge the staff of the Fermilab Technical Division for their continued assistance.

REFERENCES

- [1] R. Bossert et al., “Development of a High Gradient Quadrupole for the LHC Interaction Regions”, *IEEE Transactions on Applied Superconductivity*, Vol 7, No 2, June 1997, p.751
- [2] R. Bossert et al., “Fabrication of the First Short Model of High Gradient Quadrupole for the LHC Interaction Regions”, *MT-15 Proceedings*, 1997
- [3] R. Bossert et al., “Design, Development and Test of 2m Quadrupole Model Magnets for the LHC Inner Triplet”, *IEEE Transactions on Applied Superconductivity*, Vol 9, No 2, June 1999
- [4] N. Andreev et al., “Recent Quench Performance of Fermilab High Gradient Quadrupole Short Models for the LHC Interaction Region”, *1999 Particle Accelerator Conference*, in press.
- [5] N. Andreev et al., “Study of Kapton Insulated Superconducting Coils Manufactured for the LHC Inner Triplet Model Magnets at Fermilab”, *MT16 Proceedings*, 1999, in press.
- [6] N. Andreev et al., “Mechanical Design and Analysis of LHC Inner Triplet Quadrupole Magnets at Fermilab”, *MT16 Proceedings*, 1999, in press.
- [7] N. Andreev et al., “Quench Behavior of Quadrupole Model Magnets for the LHC Inner Triplets at Fermilab”, *MT16 Proceedings*, 1999, in press.
- [8] R. Bossert et al., “Quench Protection Studies of the LHC Interaction Region Quadrupoles at Fermilab”, *MT16 Proceedings*, 1999, in press.
- [9] J. DiMarco et al., “Correction of High Gradient Quadrupole Harmonics with Magnetic Shims”, *MT16 Proceedings*, 1999, in press.
- [10] N. Andreev et al., “Field Quality in Fermilab-built Models of High Gradient Quadrupole Magnets for the LHC Interaction Regions”, *MT16 Proceedings*, 1999, in press.